

(19) World Intellectual Property Organization  
International Bureau



(43) International Publication Date  
14 February 2002 (14.02.2002)

PCT

(10) International Publication Number  
**WO 02/13273 A1**

(51) International Patent Classification<sup>7</sup>: **H01L 29/06**

(21) International Application Number: **PCT/US01/23052**

(22) International Filing Date: **23 July 2001 (23.07.2001)**

(25) Filing Language: **English**

(26) Publication Language: **English**

(30) Priority Data:  
**09/633,598 7 August 2000 (07.08.2000) US**

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(81) Designated States (*national*): AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW.

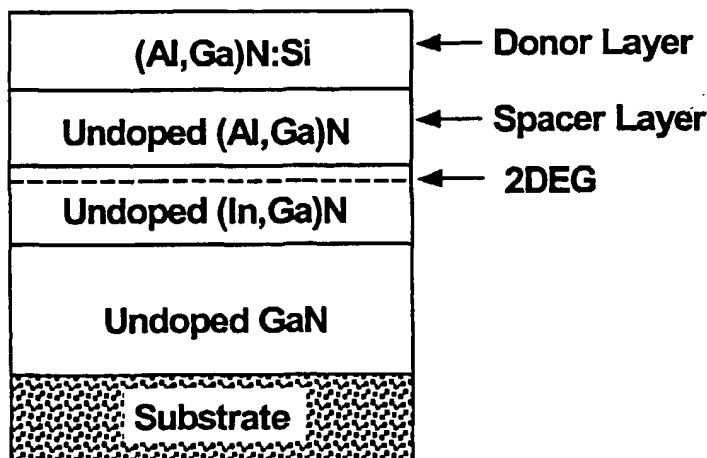
(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— with international search report

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(54) Title: **INDIUM GALLIUM NITRIDE CHANNEL HIGH ELECTRON MOBILITY TRANSISTORS, AND METHOD OF MAKING THE SAME**



(57) Abstract: A gallium nitride-based HEMT device, comprising a channel layer formed of an InGa<sub>N</sub> alloy. Such device may comprising an AlGa<sub>N</sub>/InGa<sub>N</sub> heterostructure, e.g., in a structure including a GaN layer, an InGa<sub>N</sub> layer over the GaN layer, and a (doped or undoped) Al-GaN layer over the InGa<sub>N</sub> layer. Alternatively, the HEMT device of the invention may be fabricated as a device which does not comprise any aluminum-containing layer, e.g., a GaN/InGa<sub>N</sub> HEMT device or an InGa<sub>N</sub>/InGa<sub>N</sub> HEMT device.

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**INDIUM GALLIUM NITRIDE CHANNEL HIGH ELECTRON MOBILITY  
TRANSISTORS, AND METHOD OF MAKING THE SAME**

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**GOVERNMENT RIGHTS IN INVENTION**

The invention was made in the performance of the U.S. Army Space and Missile  
Defense Command, Contract Number DASG60-98-C-0025. The government has  
10 certain rights in the invention.

**BACKGROUND OF THE INVENTION**

15 **Field Of The Invention**

This invention relates to high electron mobility transistor (HEMT) devices and method  
of making the same.

20 **Description of the Related Art**

GaN based materials have physical and electronic properties that make them attractive  
for high temperature, high power and high frequency devices. Wide bandgap  
25 semiconductors (GaN and SiC) have inherently lower thermal carrier generation rates  
and higher breakdown fields compared to Si and GaAs, as shown in Table 1 below.

Table 1

Properties of candidate materials for high power, high temperature, high frequency electronic devices

Material Property	Si	GaAs	4H-SiC	GaN
Bandgap (eV)	1.1	1.4	3.3	3.4
Breakdown field ( $10^5$ V/cm)	2	4	30	30?
Electron mobility ( $\text{cm}^2/\text{Vs}$ )	1400	8500	800	900 <sup>a</sup> , 2000 <sup>b</sup>
Maximum velocity ( $10^7$ cm/s)	1	2	2	3
Thermal conductivity (W/cm K)	1.5	0.5	4.9	1.3

5 (a) for  $n = 5 \times 10^{16} \text{ cm}^{-3}$ ; (b) for an AlGaIn/GaN structure

GaN has additional advantages including a high ( $> 800 \text{ cm}^2/\text{Vs}$ ) electron mobility and a high ( $> 10^7 \text{ cm/sec}$ ) electron velocity. Furthermore, high electron mobility transistors (HEMTs) which offer higher mobilities, better charge confinement and higher  
 10 breakdown voltages can be fabricated in the AlGaIn/GaN materials system. Room temperature radio frequency (8-10 GHz) output powers on the order of 6-8 W/mm are theoretically possible in the AlGaIn/GaN materials system and power densities as high as 6.8 W/mm have recently been reported (S.T. Sheppard, et al., 56<sup>th</sup> Device Research Conference, Charlottesville, VA, June 22-24, 1998).

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While promising output powers have been reported in AlGaIn/GaN HEMTs, materials-related issues continue to limit device performance. Persistent photoconductivity (PPC) and drain I-V collapse have been reported in AlGaIn alloys (M.D. McCluskey, N.M. Johnson, C.G Van De Walle, D.P. Bour, M. Kneissl and W. Walukiewicz, *Mat. Res. Soc. Symp. Proc.* 521 (1998), p. 531) and AlGaIn/GaN heterostructures (J.Z. Li,  
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J.Y. Lin, H.X. Jiang, M. A. Khan and Q. Chen, *J. Appl. Phys.* 82 (1997) 1227). These effects arise from carrier trapping and generation from deep levels in the material and can lead to poor high frequency performance, decreased drain currents and reduced output powers in a HEMT. PPC and current collapse in GaAs-based HEMTs have been attributed to defect-donor complexes (DX centers) in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  when  $x > 0.20$ . Evidence for oxygen DX-centers in Al-rich  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  ( $x > 0.27$ ) has recently been reported (M.D. McCluskey, et al., *ibid.*). High Al content AlGaN layers ( $x > 0.20$ ) are commonly used to achieve high sheet densities in AlGaN/GaN HEMT structures via piezoelectric-induced doping as shown by the data in Figure 1, which is a plot of sheet density as a function of percent aluminum composition in undoped 23 nanometer AlGaN/GaN heterostructures.

In order to further improve the performance of III-V nitride HEMTs, methods must be identified to reduce or eliminate the deleterious effects of deep level defects that result from the use of high-Al composition layers.

### SUMMARY OF THE INVENTION

The present invention relates in one aspect thereof to a gallium nitride-based HEMT device, comprising a channel layer formed of an InGaN alloy.

Such device may comprise an AlGaN/InGaN heterostructure, e.g., in a structure including a GaN layer, an InGaN layer over the GaN layer, and an AlGaN layer over the InGaN layer. The AlGaN layer may be doped or undoped, as necessary or desired in a given end use application of the HEMT.

Alternatively, the HEMT device of the invention may be fabricated as a device which does not comprise any aluminum-containing layer, e.g., a GaN/InGaN HEMT device or an InGaN/InGaN HEMT device.

- 5 In another aspect, the invention relates to a method of fabricating a GaN-based HEMT device, comprising forming a channel layer for the device of an InGaN alloy.

Other aspects, features and embodiments of the invention will be more fully apparent from the ensuing disclosure and appended claims.

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#### **BRIEF DESCRIPTION OF THE DRAWINGS**

- Figure 1 is a plot of sheet density versus % Al in undoped 23 nm AlGa<sub>N</sub>/Ga<sub>N</sub> heterostructures, showing that piezoelectric-induced doping results in an increase in  
15 sheet density with increasing Al composition.

Figure 2 is a schematic representation of an AlGa<sub>N</sub>/InGa<sub>N</sub> HEMT structure.

Figure 3 is a band diagram of an AlGa<sub>N</sub>/InGa<sub>N</sub> HEMT structure.

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#### **DETAILED DESCRIPTION OF THE INVENTION, AND PREFERRED EMBODIMENTS THEREOF**

- In accordance with the present invention, the performance of GaN-based HEMTs is  
25 improved by use of InGa<sub>N</sub> alloys in the channel layer of the device.

The use of InGaN alloys in the channel layer of HEMT devices has been discovered to permit substantially lower Al composition AlGa<sub>N</sub> layers to be employed at equivalent levels of strain and piezoelectric doping characteristic of AlGa<sub>N</sub>/Ga<sub>N</sub> heterostructures.

5 InGa<sub>N</sub> provides a large a-lattice constant in relation to Ga<sub>N</sub> (the a-lattice constant difference between Ga<sub>N</sub> and In<sub>N</sub> is 0.351Å, compared to a 0.079Å difference between Ga<sub>N</sub> and Al<sub>N</sub>), and low Al and In content layers can be used to produce pseudomorphic AlGa<sub>N</sub>/InGa<sub>N</sub> heterostructures with comparable strain to AlGa<sub>N</sub>/Ga<sub>N</sub>. For example, the lattice mismatch of an Al<sub>0.10</sub>Ga<sub>0.90</sub>N/In<sub>0.046</sub>Ga<sub>0.954</sub>N interface is  
10 identical to that of Al<sub>0.30</sub>Ga<sub>0.70</sub>N/Ga<sub>N</sub>. Consequently, it is possible to produce AlGa<sub>N</sub>/InGa<sub>N</sub> heterostructures that enable the use of reduced Al content AlGa<sub>N</sub> layers without significant reductions in piezoelectric-induced doping or degradation of the structural or electrical properties of the channel layer.

15 In addition to a reduction in DX-center related transient effects, the use of low Al content AlGa<sub>N</sub> layers in the HEMT enables reduced ohmic contact resistance to be achieved.

The high electron mobility of In<sub>N</sub> (4000 cm<sup>2</sup>/Vs for n=1E16 cm<sup>-3</sup>) in relation to Ga<sub>N</sub>  
20 permits the use of InGa<sub>N</sub> alloys in the channel layer of the device to significant improvements in electrical properties and device performance.

Figure 2 is a schematic representation of an AlGa<sub>N</sub>/InGa<sub>N</sub> HEMT structure for an illustrative device according to the present invention. In the fabrication of this device,  
25 a pseudomorphic AlGa<sub>N</sub> layer is grown on top of an InGa<sub>N</sub> layer overlying a Ga<sub>N</sub>

layer, using appropriate growth conditions readily determinable without undue experimentation by those of ordinary skill in the art. The InGaN layer should be thick enough so that it is "relaxed" in the multilayer structure. Typical thicknesses in various embodiments of the invention may include thicknesses of the InGaN layer in the range  
5 of from about 100 to about 5,000 nanometers, with more specific thicknesses in some instances being in the range of from about 200 to about 2,000 nanometers, or in a narrower range of from about 400 to about 1,000 nanometers.

Alternatively, the InGaN layer can be grown directly on the substrate (including a  
10 buffer layer). The AlGaN layer can be undoped or the upper or top-most portion of the AlGaN can be doped to further increase the sheet density.

Alternatively, an InGaN channel HEMT can be fabricated using GaN or InGaN on InGaN. In this case, chemically reactive Al-containing layers are completely  
15 eliminated from the device structure, to provide a GaN/InGaN HEMT with improved long-term stability and reliability characteristics under high power operation than are achievable by an AlGaN/GaN HEMT or an AlGaN/InGaN HEMT. Additionally, an InGaN/InGaN HEMT provides fabrication advantages due to the differing optimum growth conditions between InGaN, and AlGaN or GaN.

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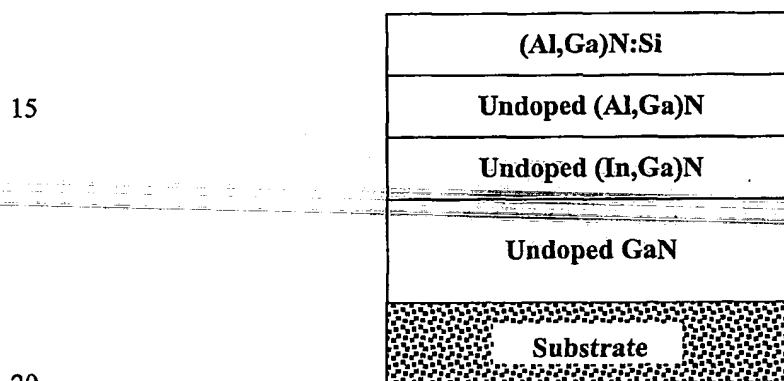
The growth of the indium gallium nitride layers in the practice of the invention may be effected by any suitable process or technique therefor. For example, such layers may be formed by vapor phase techniques in which reactant gas species (e.g., ammonia, trimethylgallium, and trimethylindium) enter a growth reactor that contains the  
25 substrate. The reactant gas species passes over the substrate depositing an epitaxial

film of said species (i.e., nitrogen from ammonia, gallium from trimethylgallium, and indium from trimethylindium). The InGaN process may occur at temperatures in the range of from about 500 to 1000°C, with a more specific temperature range of from about 700 to 950°C, or in a narrower temperature range of from about 800 to 900°C.

- 5 The pressure of the reactor may be maintained in the range of from about 50 to 980mbarr. The indium-to-gallium ratio may be anywhere in the range of from 0 to 100%.

The features, aspects and advantages of the present invention are further shown with  
10 reference to the following non-limiting examples relating to the invention.

#### EXAMPLE 1



**Example of the fabrication of an HEMT structure of the type shown in Figure 2**

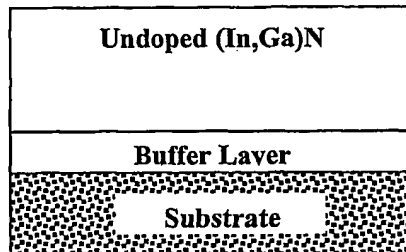
A HEMT structure of the design shown in Example 1 comprises a suitable substrate for depositing GaN; an unintentionally doped GaN layer as a buffer over said substrate; an  
25 unintentionally doped InGaN channel layer over said GaN buffer layer that is relaxed with respect to strain due to the different lattice constants of the said GaN buffer layer and the InGaN channel layer; an unintentionally doped AlGaN spacer layer over said



InGaN channel layer; an intentionally silicon-doped AlGaN donor layer over said AlGaN spacer layer.

**EXAMPLE 2**

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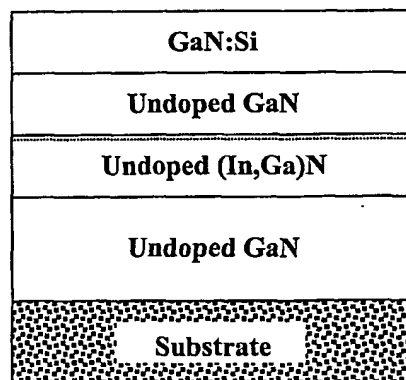
**Example of the fabrication of the InGaN layer being formed directly on a substrate, with a buffer layer**

An InGaN structure of the design shown in Example 2 comprises a suitable substrate for depositing GaN; a buffer layer over said substrate; an unintentionally doped InGaN layer over said buffer layer.

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**EXAMPLE 3**

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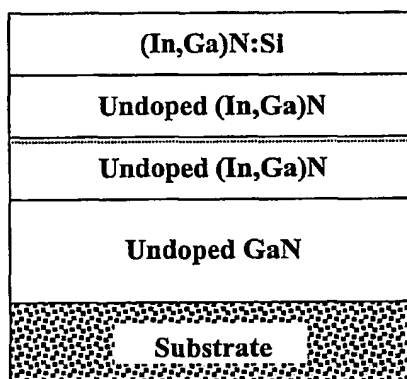
**Example of the fabrication of a GaN/InGaN HEMT device**

A HEMT structure of the design shown in Example 3 comprises a suitable substrate for depositing GaN; an unintentionally doped GaN layer as a buffer over said substrate; an unintentionally doped InGaN channel layer over said GaN buffer layer that is relaxed with respect to strain due to the different lattice constants of the said GaN buffer layer and the InGaN channel layer; an unintentionally doped GaN spacer layer over said InGaN channel layer; an intentionally silicon-doped GaN donor layer over said AlGaN spacer layer.

#### EXAMPLE 4

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#### **Example of the fabrication of an InGaN/InGaN HEMT device**

A HEMT structure of the design shown in Example 4 comprises a suitable substrate for depositing GaN; an unintentionally doped GaN layer as a buffer over said substrate; an unintentionally doped InGaN channel layer over said GaN buffer layer that is relaxed with respect to strain due to the different lattice constants of the said GaN buffer layer and the InGaN channel layer; an unintentionally doped InGaN spacer layer that has a lower InN concentration compared to the InGaN channel layer over said InGaN channel layer; an intentionally silicon-doped InGaN donor layer over said InGaN spacer layer that has the same InN concentration as the InGaN spacer layer. In this example, the channel comprising the high density of charged carriers is formed at or

near the interface between the InGaN channel layer and InGaN spacer layer due to the piezoelectric-induced doping as a result of the strain associated with the differing InN concentrations of the InGaN channel layer and InGaN spacer layer.

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Although the invention has been variously disclosed herein with reference to illustrative embodiments and features, it will be appreciated that the embodiments and features described hereinabove are not intended to limit the invention, and that other  
10 variations, modifications and other embodiments will suggest themselves to those of ordinary skill in the art. The invention therefore is to be broadly construed, consistent with the claims hereafter set forth.

**THE CLAIMS****What Is Claimed Is:**

- 5     1.     A gallium nitride-based HEMT device, comprising a channel layer formed of an InGaN alloy.
2.     The device of claim 1, comprising an AlGaN/InGaN heterostructure.
- 10    3.     The device of claim 1, comprising a GaN layer, an InGaN layer over the GaN layer, and an AlGaN layer over the InGaN layer.
4.     The device of claim 1, which does not comprise an aluminum-containing layer.
- 15    5.     The device of claim 4, comprising a GaN/InGaN HEMT.
6.     ~~The device of claim 4, comprising an InGaN/InGaN HEMT.~~
7.     The device of claim 1, comprising an AlGaN layer.
- 20    8.     The device of claim 7, wherein the AlGaN layer is undoped.
9.     The device of claim 7, wherein the AlGaN layer is doped with a dopant increasing the sheet density thereof.
- 25    10.    A method of fabricating a GaN-based HEMT device, comprising forming a channel layer for said device of an InGaN alloy.

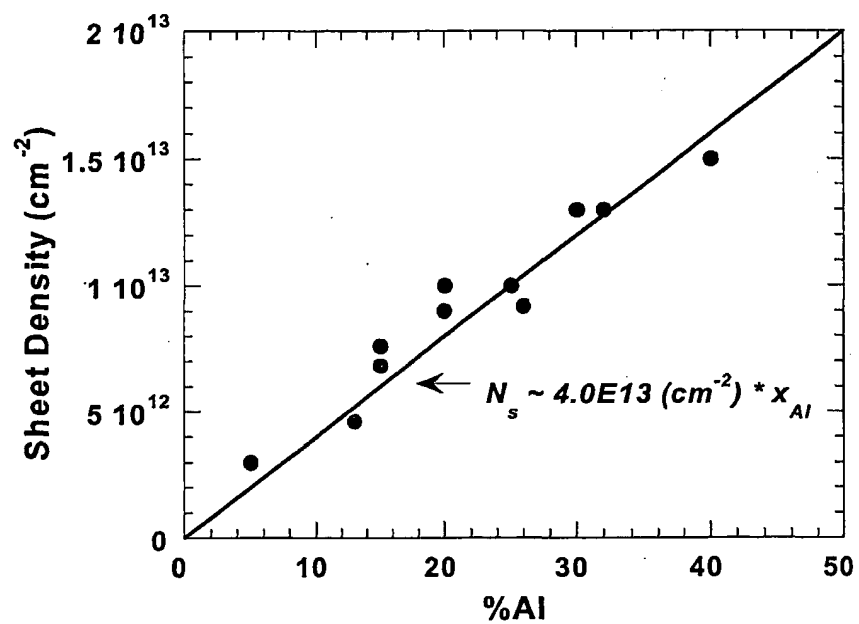


Figure 1

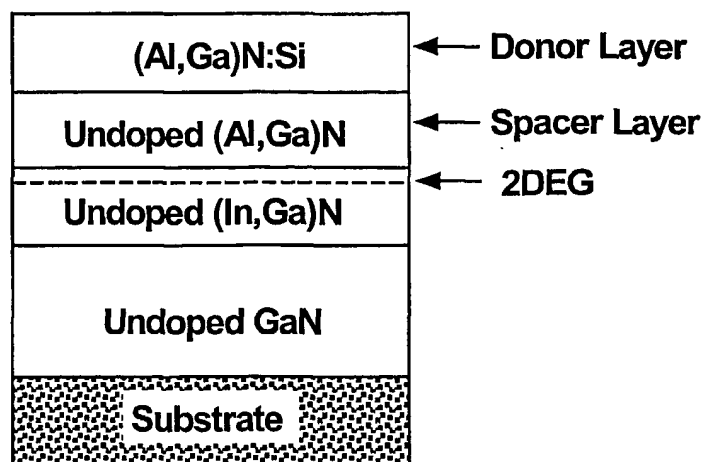


Figure 2

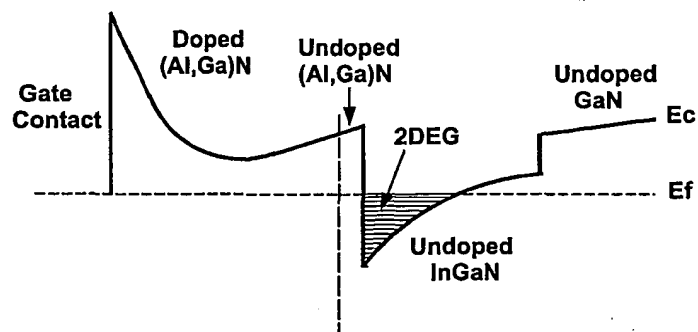


Figure 3

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US01/23052

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(7) : H01L 29/06

US CL : 257/20

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 257/22, 24, 27, 76, 190, 192, 194, 201, 284

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched  
NONEElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)  
USPTO APS EAST/IS&R, BRS**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 11-274474 A (MAEDA et al) 08 October 1999 (08.10.1999), the entire reference.	1, 2, 4, 5, 7, 8, 10
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Y		3, 6, 9
Y,P	US 6,172,382 B1 (NAGAHAMA et al) 09 January 2001 (09.01.2001), the entire reference.	3, 6, 9

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

## \* Special categories of cited documents:

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Date of the actual completion of the international search

20 August 2001 (20.08.2001)

Date of mailing of the international search report

14 SEP 2001

Name and mailing address of the ISA/US

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